

Thermal Protection System of the HUYGENS probe for TITAN entry: qualification, flight preparation and lessons learnt

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PRESENTATION OUTLINE

⇒ Mission preparation phase

- **AQ60 possible transparency**
 - » **Representativeness of IRS tests**
 - » **Low intensity UV exposure tests (ESA/ESTEC)**
 - » **High intensity UV exposure tests (NASA)**
- **Influence of heat flux update on TPS**
 - » **General logic of thermal qualification tests performed during development phase**
 - » **Validation of thermal model**

⇒ Lessons learnt

⇒ Concluding Remarks

FLIGHT PREPARATION

MISSION PREPARATION PHASE

- ⇒ Final definition of mission parameters carried out in 2004.
- ⇒ The performance of the thermal shield was one among the parameters addressed at system level
 - Need for a reassessment of the thermal response of the TPS
 - » review of the tests performed during the development phase
 - » thermal computations supporting risk analysis
 - taking into account some updated information that was not yet available during the development phase 10 years before.
- ⇒ More particularly, two points were considered:
 - A possible transparency of the AQ60 material in the UV wavelengths
 - Updated heat fluxes, with expected values significantly higher than during the development phase.

AQ60 possible transparency

- ⇒ Heat shield undergoes both convective and radiative heat fluxes.
- ⇒ Radiative emission of the shock layer occurs in the narrow UV band (~380nm)
- ⇒ In the framework of studies about aerocapture mission at Titan, NASA experts identified possible uncertainties on performance of lightweight materials exposed to radiative heating
 - Radiation wavelength ➡ ⇒ absorption length ➤
- ⇒ no available test result in UV wavelength for lightweight materials
- ⇒ Potential for in-depth absorption could be of concern for AQ60, (char spallation, reduced efficiency, eventual additional heating of the substructure...)

- ⇒ Action plan
 - Status on representativeness of development phase tests
 - Status on representativeness of IRS test wrt radiative UV emission
 - Low intensity radiation exposure tests at ESTEC
 - High intensity radiation exposure tests at NASA

Representativeness of IRS tests

- ⇒ Only IRS tests can be relevant with regard to UV radiation (other tests = infrared heating or plasma tests with a pure N₂ atmosphere)
- ⇒ During the development phase, this problem of UV radiation had not been considered, and only the total heat flux had been measured
- ⇒ Not retained : theoretical analyses, new exploitation of 1992 tests, new tests
- ⇒ extensive characterization of Nitrogen/Methane plasma flows was undertaken by IRS from 1992 to 1998 (after Huygens test campaign)
 - A specific radiometer was developed to measure the radiation emitted by the flow
 - In addition, a set of emission spectroscopy measurements was done for various combinations of N₂/CH₄ mixtures
 - Radiative heat flux observed during these experiments, with some emission around 380 nm (CN violet)
 - A direct quantitative interpretation of these tests is not easy (local measurements in reduced solid angles)
 - Estimated integrated value of the radiative heat flux = 377 kW/m², which represents ≈20% of the corresponding total heat flux equal to 1800 kW/m².

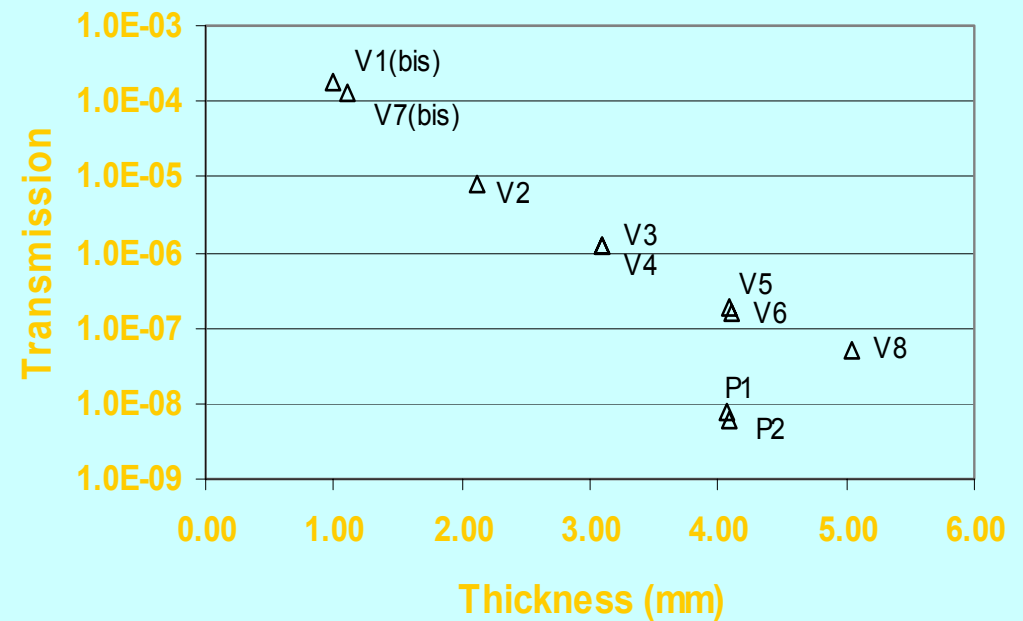
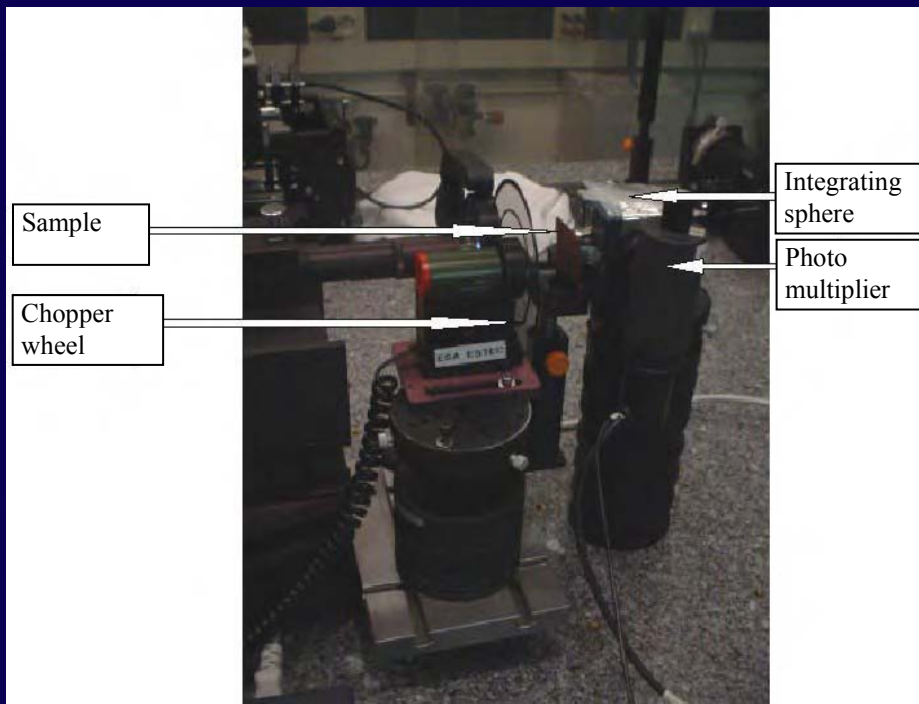
⇒ **significant radiative component of the flux for 1992 tests**

⇒ **no identified evident influence on material behavior**

POSITIVE RESULT, even though the worst expected value of the radiative heat flux could be higher than the experienced one

Low intensity UV exposure tests (ESA/ESTEC)

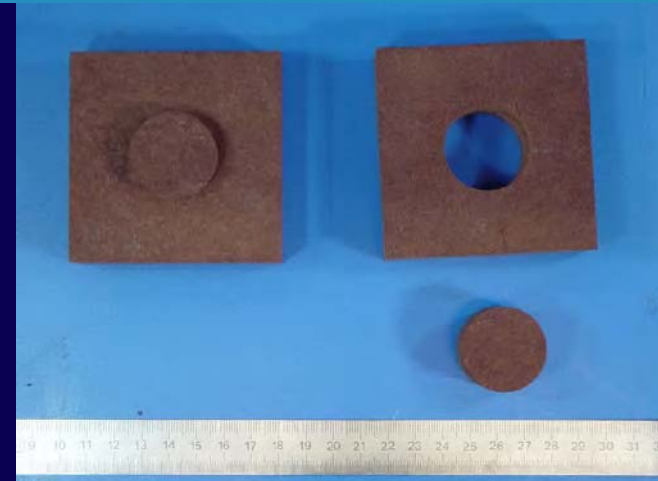
- ⇒ AQ60 samples of 40 x 40 mm x 1 to 5 mm thick
- ⇒ spectral Xenon lamp radiating at a wavelength of 377 nm
- ⇒ light transmitted through the samples was recorded
- ⇒ Very low transmission measured, even lower for charred AQ60



High intensity UV exposure tests + complementary arc jet test (NASA) (1/2)

- ⇒ In order to evaluate the performance of candidate Titan lightweight TP materials exposed to UV radiation, NASA has developed a specific facility based on a high-power Mercury-Xenon lamp (strong emission in the UV range)
- ⇒ NASA offered to include AQ60 samples in a test campaign prepared at NASA Ames
- ⇒ To complete the low intensity results by tests at high temperature was very relevant
- ⇒ Opportunity to get in-depth temperature evolutions
- ⇒ Complementary elementary characterisation and arc jet test performed with unused test samples

8 AQ60 samples (75 x 75 x 20 mm)
provided by EADS-ST
central plug insert (diameter 30mm)
For thermocouples installation by NASA

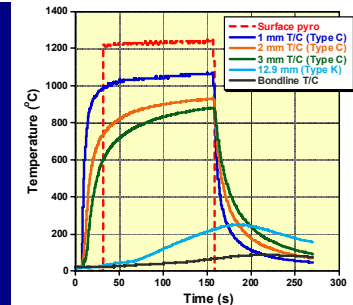


High intensity UV exposure tests + complementary arc jet test (NASA) (2/2)

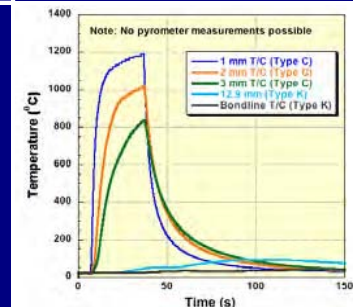
MAIN CONCLUSIONS

- ⇒ Very good behavior of the material
- ⇒ Demonstration that there is no transparence at UV wavelengths, and that the material absorbs this radiation at the surface
- ⇒ No surface recession during arc jet test
- ⇒ Exploitation still on-going
 - Consolidation of thermal model of AQ60
 - Comparison of NASA and EADS analyses
 - Pressure effects on thermal conductivity

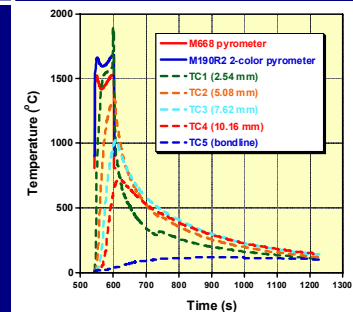
UV test at 50 W/cm²
150 sec.
August 2004



UV test at 150 W/cm²
30 sec.
November 2004



Arc jet test
80 W/cm²
57 sec.
December 13th 2004



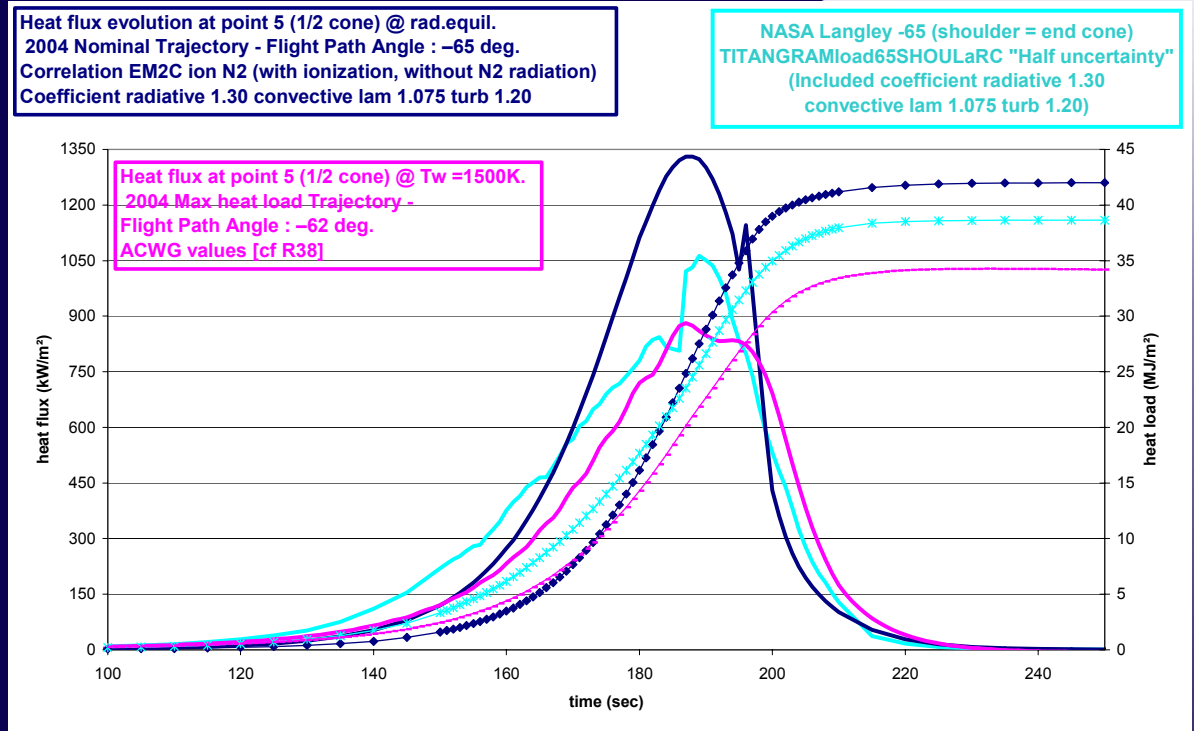
Influence of heat flux update on TPS - overall context

- ⇒ **Needed update of the mission and refinement of the entry corridor:**
 - **Communications between orbiter and probe**
 - **Selection of a new atmosphere model (Yelle) associated to the Strobel Gravity Wave model**
 - **The associated aerothermal environment was therefore rather different from the one used during phase C/D.**

- ⇒ **First reassessment work performed in 2003 by the industrial team**
 - **reviewed in February 2004 (Delta Flight Acceptance Review)**
 - **During this Δ FAR, different heating levels have been observed between various contributions, namely EADS-ST, ESTEC-MPA and NASA ARC**
 - **Creation of an Aeroheating Convergence Working Group(ACWG) EM2C, EADS-ST, ESTEC-MPA, NASA Langley & ARC**
 - » **After a correct understanding of the differences, to reconcile the various aerothermal inputs and consolidate a single aerothermal environment.**

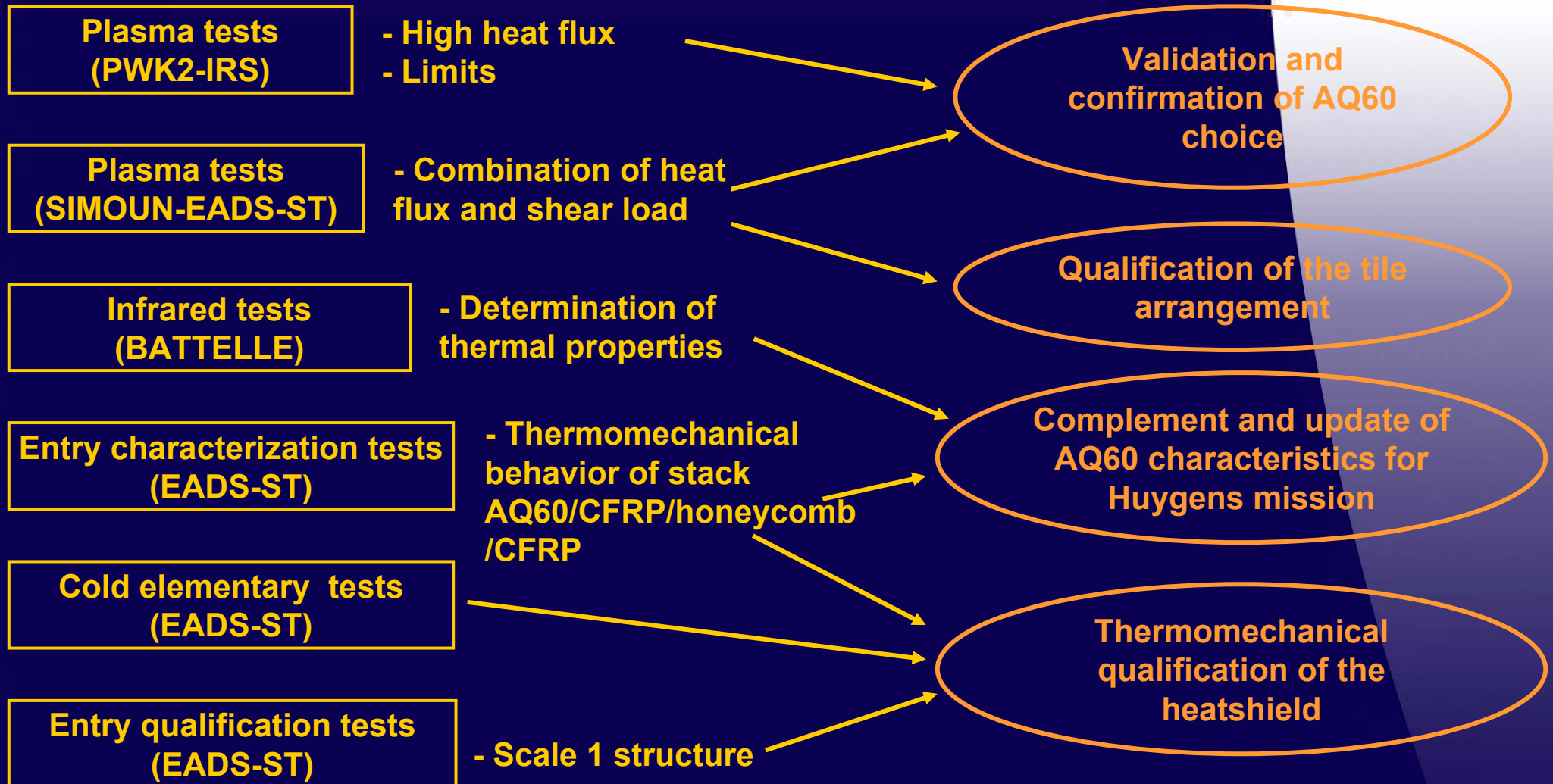
Influence of heat flux update on TPS - summary of the main actions

- ⇒ Update of heat flux up to the end of November 2004
 - Taking into account last update of atmosphere models, brought by Titan flyby on July 3rd & October 26th
- ⇒ Influence of this heat flux update on TPS thermal response analysed as soon as heat flux data were available
- ⇒ Higher values than during development phase
- ⇒ Review of qualification level and TPS performance
- ⇒ Risk & reliability assessment



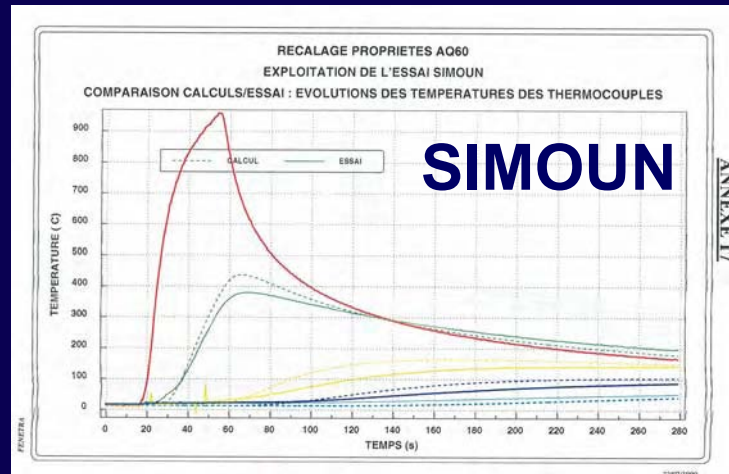
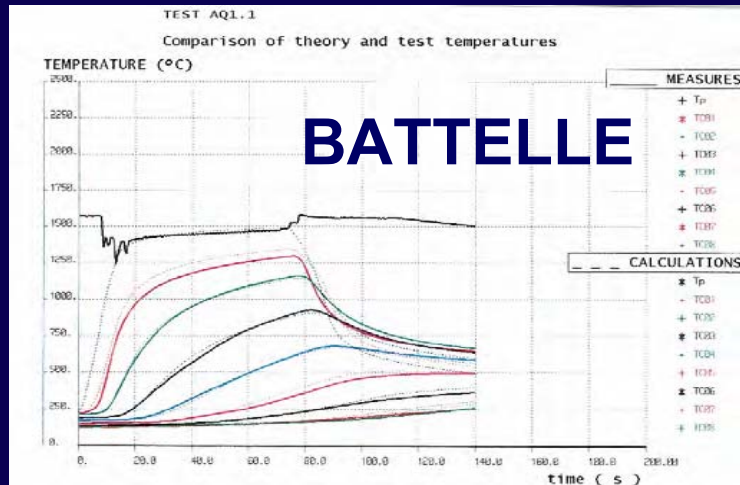
Entry characteristics (development phase values)
 Duration ~300 sec.
 Max. heat flux (front face) 1400 kW/m² (20 sec.)
 max. heat flux (rear face) 30 to 120 kW/m²
 max. shear stress 135 Pa
 (area close to edge of decelerator)
 max. pressure 0.1 atm. (stagn. point)
 worst atmosphere 77% N₂, 20% Ar, 3% CH₄

GENERAL LOGIC OF QUALIFICATION TESTS



Validation of thermal model

Good restitution of temperatures measured during tests

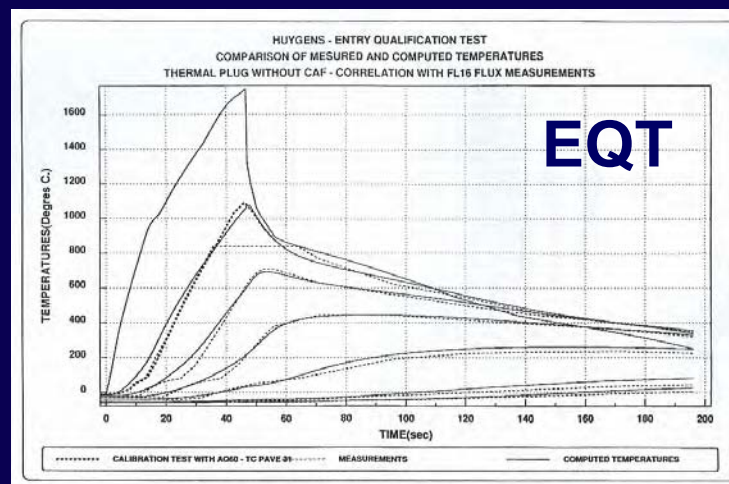
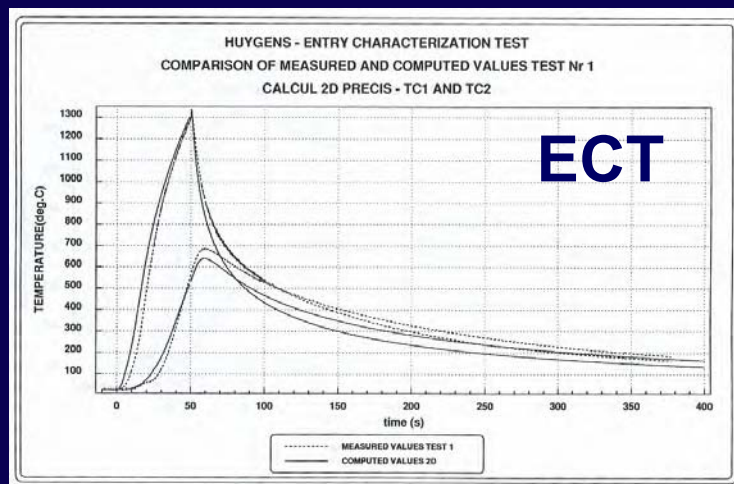


BUT

Too similar
test conditions

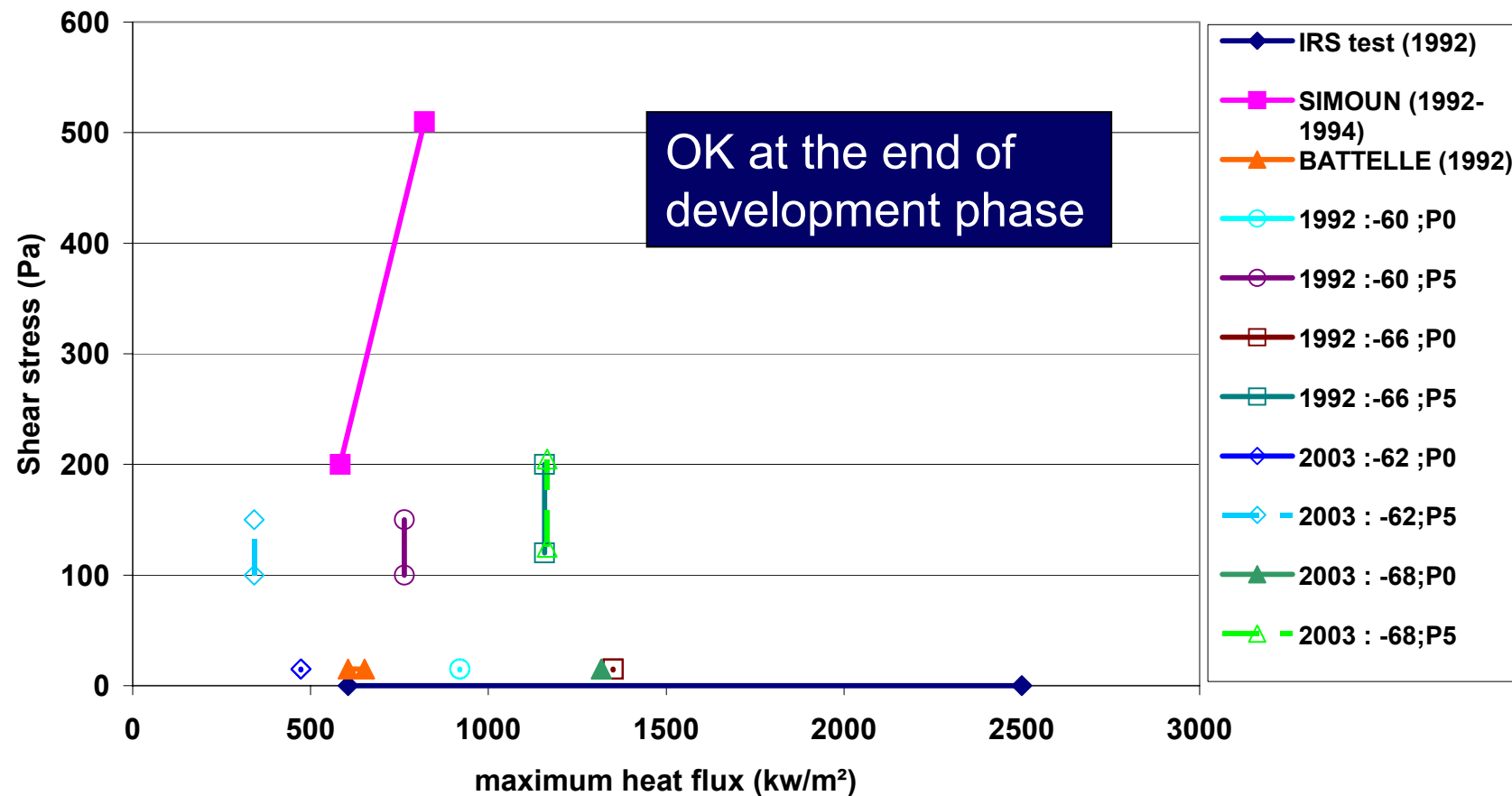
Low heat flux

Only internal
heat transfer



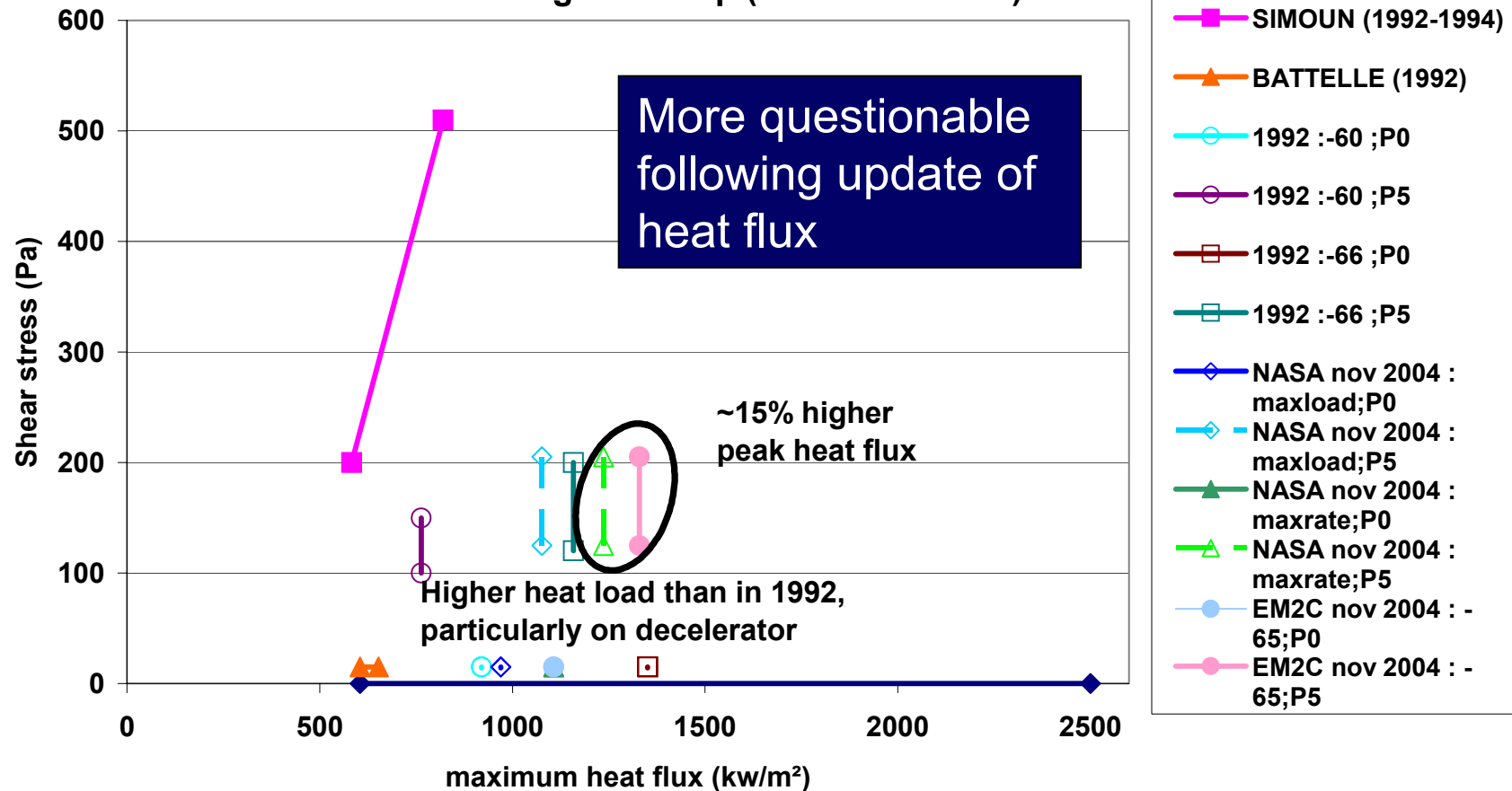
Heat Flux : Qualification domain (1/2)

Comparison of specified flight environment with qualification domain
Status at end of development phase and at Delta-FAR (February 2004)



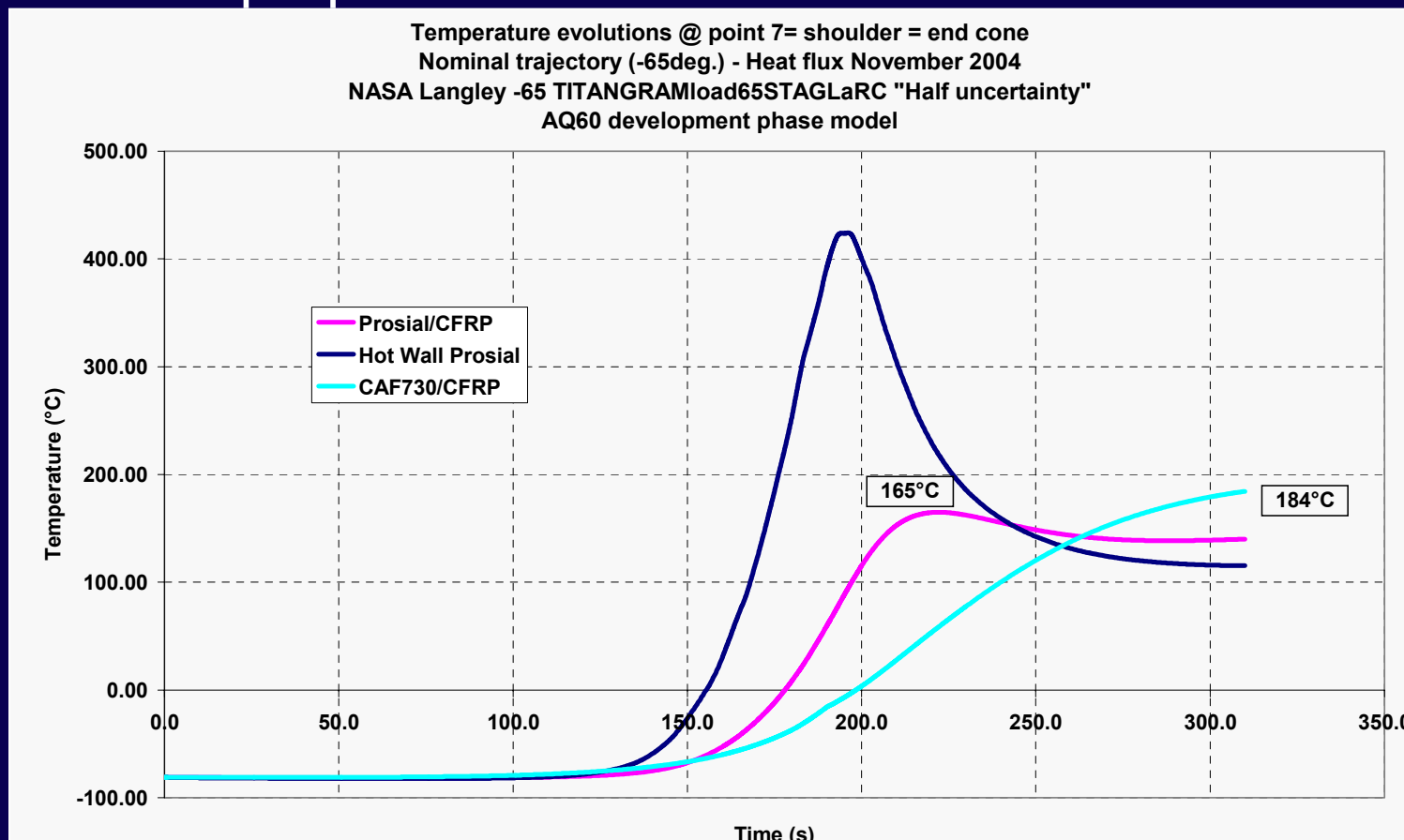
Heat Flux : Qualification domain (2/2)

Comparison of specified flight environment
with qualification domain
Status during final loop (November 2004)



Temperature evaluations

Most critical part = decelerator zone of Frontshield
Analyses accounting for uncertainties on heat flux and material properties



Above allowable values in some cases

Need to be assessed at system level

Margins Analysis Matrix (December 2004)

TPS Thermal Response Uncertainty

20%	Forebody	Forebody	Forebody
	Aftbody	Aftbody	Aftbody
10%	Forebody	Forebody	Forebody
	Aftbody	Aftbody	Aftbody
0%	Forebody	Forebody	Forebody
	Aftbody	Aftbody	Aftbody
	None	Half	Full
	Aerothermal Environment Uncertainty		



Margin < 0 deg.



0 < Margin < 15 deg.



Margin > 15 deg.

Margins Analysis Matrix (December 2004)

TPS Thermal Response Uncertainty

20%	A20 - Margin Forebody >19°C Aftbody >15°C	B20 – Margin Forebody >5°C Aftbody >7°C	C20 – Margin Forebody <0°C Aftbody <0°C
10%	A10 - Margin Comfortable Based on A20	B10 - Margin Forebody: 26°C Aftbody >16°C	C10 - Margin Forebody: 9°C Aftbody >1°C
0%	A0 - Margin Forebody >42°C Aftbody >34°C	B0 - Margin Comfortable Based on B10	C0 – Margin Forebody >20°C Aftbody >10°C
	None	Half	Full

Aerothermal Environment Uncertainty

CONCLUSION of FLIGHT PREPARATION PHASE



Reassessment of TPS performance

Review of development phase qualification

Review of TPS/structure adherence

Complementary specific topics

⇒ **Confidence in material behaviour in spite of some lack of relevant experimental results**

⇒ **Red flag at TPS level turned to green lights**

⇒ **READY TO OPERATE FOR ENTRY MISSION AT TITAN**

LESSONS LEARNT

Some considerations following fruitful cooperation with NASA in 2004

- ⇒ **High pressure because most tasks were initiated following the Delta Flight Acceptance Review (feb04)**
- ⇒ **Performance of UV radiation and arc jet test**
- ⇒ **Very interesting discussions, showing differences in the development approach**
 - **Qualification approach : NASA would have carried out a more extensive test plan**
 - **TP material modelling : theoretical approach is more widely applied by NASA, compared to a more direct exploitation of test results used by EADS-ST for Huygens**
 - **Margins management : would require additional debate for eventual search of more complete harmonisation**
 - **Pressure effect on conductivity new for both NASA & EADS-ST**
 - **Design based on tiles considered more difficult to justify by NASA**

Some considerations about thermal analysis work performed in 2004

⇒ DEVELOPMENT PHASE

- The aim was to design the TPS and optimise the mass

⇒ MISSION PREPARATION PHASE

- The objective was to evaluate TPS performance, based on actual manufacturing features of the probe
- Models could be recovered and run easily, with the support of people who prepared them 10 years before
- Exploitation of inspection documentation more difficult after a long time (some helpful background knowledge is thus missing)
- Documentation was available but knowledge of key people was also valuable and very useful

- ## ⇒ Some preparation of such an exercise just after manufacturing would have helped
- (mandatory if test predictions are requested)

Specific considerations for aft body

⇒ Main attention was paid to the front face of heat shield (higher heat flux)

BUT

⇒ higher uncertainties on aft body heat flux

⇒ thermal response shows higher sensitivity compared to the fore body

- effective part of the entering heat flux is more important
- mainly due to a much lower radiative reemission σT_w^4 .

⇒ The direct consequence is a lower robustness wrt heat flux uncertainties or evolutions

QUITE A CRITICAL POINT DURING THE LAST WEEKS OF TPS PERFORMANCE REASSESSMENT

⇒ So, even though this area does not look critical at a first glance, it is compulsory to have sufficient knowledge and precise characterisation in the appropriate range to apply satisfactory optimisation and safety margin policy.

CONCLUDING RECOMMENDATIONS (TPS)

⇒ Analysis features

- Keep in mind that the background knowledge of key people is an invaluable support to the best documentation
- Need to evaluate TPS thermal response with actual manufactured values
- Need to account for the long time from development to final mission, and its consequences (e.g. software evolution)

⇒ Design features :

- Need to have heat shield instrumentation for next missions
- Need to pay more attention to rear TPS

⇒ Margin policy :

- Interest to have further discussions for harmonization between Europe and the US

⇒ Material :

- AQ60 applicable for eventual future planetary missions
- Keep an eye on the TPS look !
 - » famous “tiles color variations file”...

Concluding Remarks & Acknowledgments



- ⇒ Huygens was in 1991 the first planetary entry Program for EADS-ST, but also one of the most exciting programme & mission ever realized in the atmospheric entry field,
- ⇒ For EADS-ST, the flight success has been possible thanks to the strong implication of motivated and competent teams,
- ⇒ Previous and current experience from military and space re-entry vehicles was one essential key of the success, for both TPS and system entry and descent analyses

Concluding Remarks & Acknowledgments

Special thanks to the whole Huygens Team :
(agency, customer and partners)

- ESA
- Alcatel Space
- NASA
- EADS-ST : great pleasure and pride to be involved in this successful endeavour, with our names on Titan forever

Line J. TISNÉ
Line V. LABASTE
Line J. B. BOUQUET

Line J. L. LARTIGUE
Line D. BOUQUET
Line D. BOUQUET

Line P. PARROT
Line D. GUERATIER
Line H. JAUDEAN

Line R. C. ...
Line V. ...
Line M. ...
Line G. ...

Line D. ...
Line V. ...
Line D. ...
Line M. ...

Line HERNANDEZ-N. ...
Line BAULE ...
Line LABAYE S. ...
Line J. ...

Line TO DUBLETT
Line S. PEACHE
Line C. BOUQUET
Line D. ...

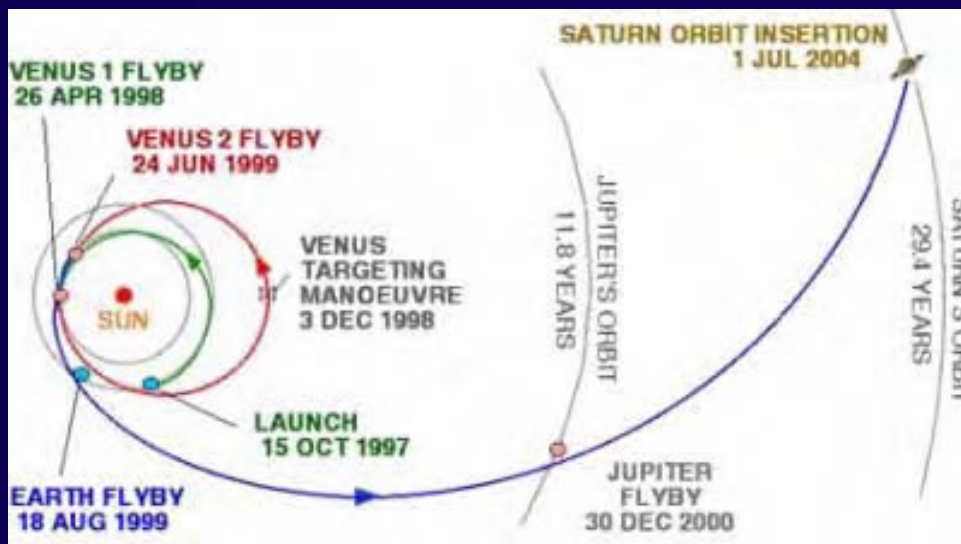
QUESTIONS ?

BACKUP SLIDES

Generalities about HUYGENS TPS

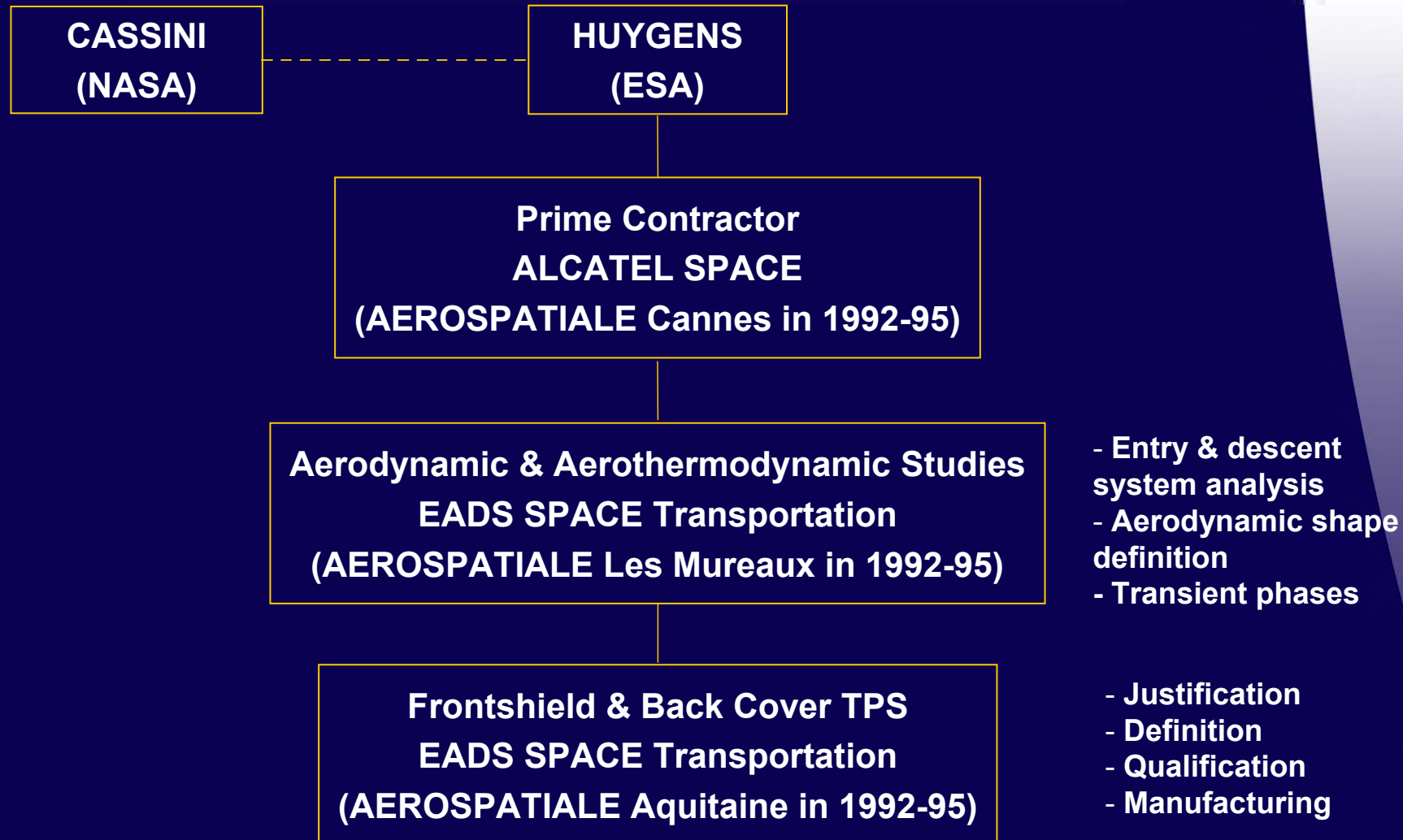
Mission, Industrial organization, TPS architecture, Entry conditions, TP materials, Qualification tests

MISSION



- ⇒ **Titan flyby**
 - **July 3rd 2004**
 - **October 26th 2004**
 - **December 13th 2004**
- ⇒ **Separation from Cassini orbiter**
 - **December 25th 2004**
- ⇒ **22-days journey to Titan**
- ⇒ **Successful entry and descent into Titan's atmosphere**
 - **January 14th 2005**

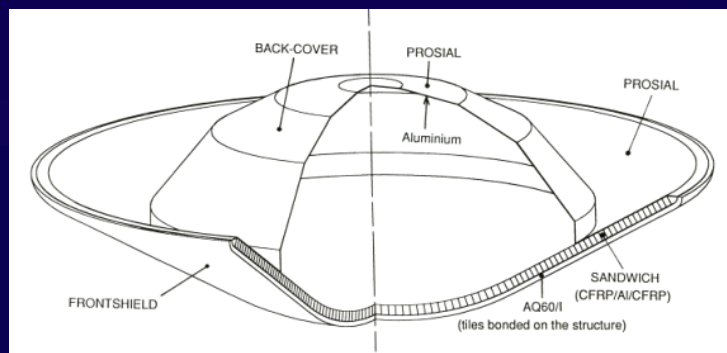
INDUSTRIAL ORGANIZATION



TPS ARCHITECTURE

⇒ FRONT SHIELD (76 kg)

- sandwich structure (aluminium honeycomb + CFRP skins) 32 kg
- 260 AQ60/I tiles on the front face bonded on the structure and jointed by a silicone glue.
 - » Thickness 17.4 to 18.2 mm
 - » 30 kg + 9 kg glue & joints
- PROSIAL on the rear face (5kg)



⇒ BACK-COVER (17kg)

- aluminum shell (0.8 mm)
- PROSIAL thermal protection (spraying process)
 - » Thickness 0.3 to 3.1 mm
 - » T.P. mass 5.2 kg



- ⇒ Total mass of the Huygens probe : 320 kg
- ⇒ Max. diameter : 2.70 m
- ⇒ Total height 0.97 m

THERMAL PROTECTION MATERIALS

Two materials developed and manufactured by EADS
SPACE Transportation

AQ60

- ⇒ Felt made of short silica fibers
- ⇒ Vacuum processing of an aqueous suspension of silica fibers and starch
- ⇒ Reinforcement with phenolic resin (AQ60/I)
- ⇒ Final density is 0.28 (volumic ratio : Silica 10%, resin 6 %, total porosity around 84 %)
- ⇒ For Huygens, machined tiles with a silicone coating
- ⇒ Pyrolysis reactions during heating
- ⇒ Good cohesion of charred layer
- ⇒ Good insulator with a high ablation temperature
- ⇒ Good mechanical properties for thermomechanical entry loads

PROSIAL 1000

- ⇒ Silicone elastomer with excellent thermal properties and silica hollow spheres
- ⇒ Density 0.54 to 0.6
- ⇒ Can directly be sprayed onto the surface to be protected



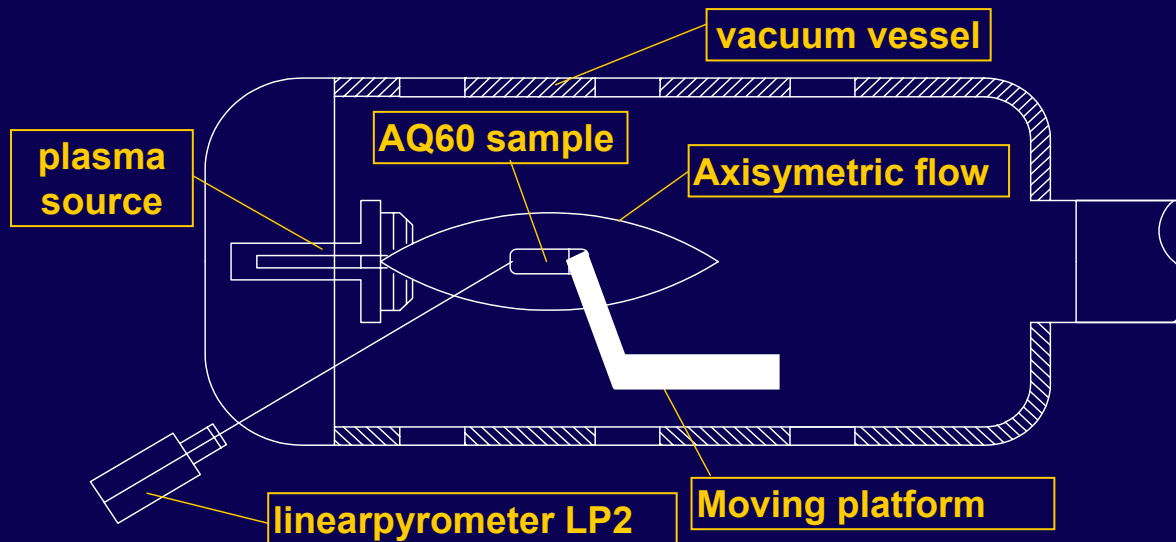
PWK2-IRS TESTS

⇒ 17 tests performed in 1992

- Stagnation point configuration
- Titan atmosphere (77% N₂, 20% Ar, 3% CH₄) & comparison with pure N₂
- Stagnation pressure: from 0.015 to 0.020 atm.
- Heat flux: from 600 to 2500 kW/m²; constant value or flight-like evolution
- Influence of coating and joints

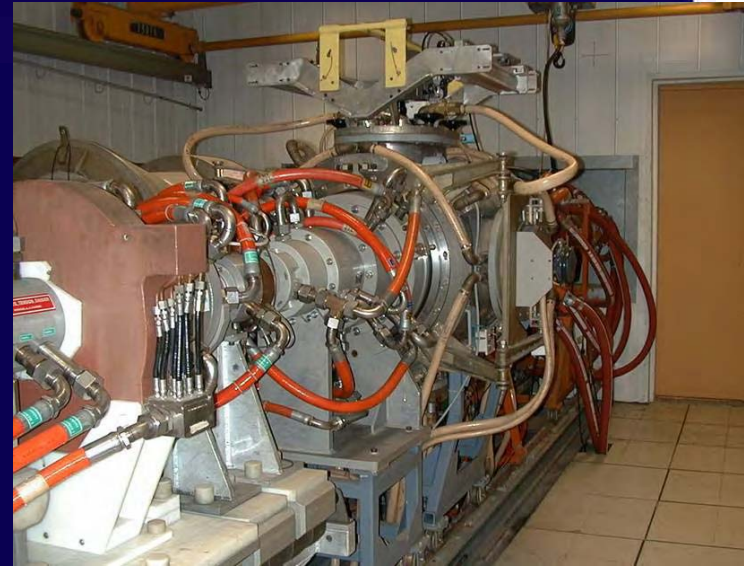
⇒ Conclusions

- good behavior of AQ60/I submitted to heat fluxes up to 2500 kW/m² in an atmosphere representative of Titan's one (77% N₂, 20% Ar, 3% CH₄).
- Satisfactory margin wrt heat flux level (limit not reached)
- good ablative behavior & determination of the corresponding ablation law



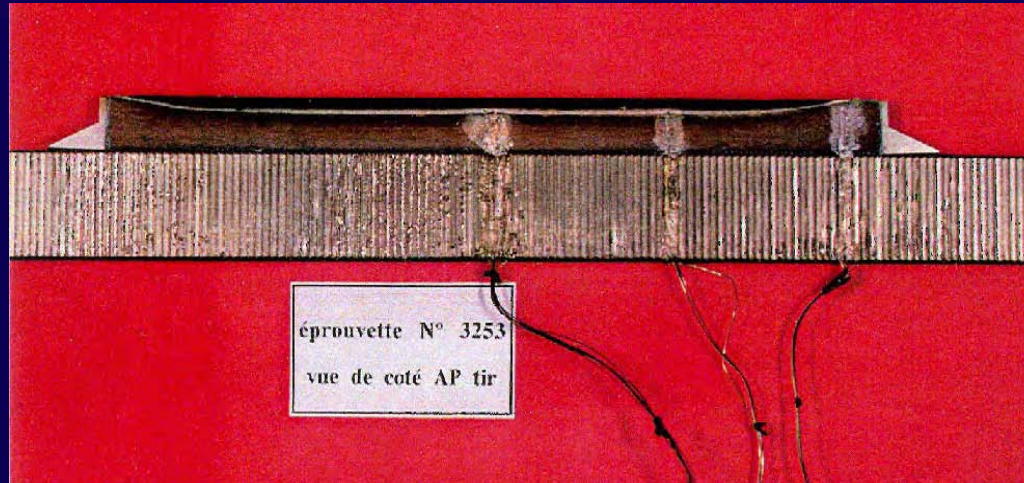
SIMOUN TESTS

- ⇒ Two series of plasma tests (1992 & 1994)
 - tangential flow configuration
 - Pure N₂ atmosphere
 - Pressure : 0.100 to 0.140 atm.
 - Shear load : 500 Pa (estimation)
 - Heat flux : 740 to 973 kW/m²
 - Samples : 300 x 300 mm
 - Board inclination : 16.5 deg.
- ⇒ Demonstration of the good behavior of the material when submitted both to heat flux and to aerodynamic shear
- ⇒ Qualification of specific points
 - MLI fixations
 - micrometeoroids holes
 - manufacturing defects (wide joints, steps or local repairs)
- ⇒ Conclusion = AQ 60 can withstand the Huygens entry conditions without any critical damage.



Entry Characterization Tests (ECT)

EADS-ST IR + mechanical facility



- ⇒ 12 samples (CFRP Honeycomb+ CAF730 glue + AQ60 with or without joint)
- ⇒ Infrared heating (0 to 775 kw/m² in 50 sec.) under N2 atmosphere
- ⇒ Tensile or compressive stressing according to the applied bending
- ⇒ Several TC on each sample submitted to thermal + mechanical mission
+ 2 samples with more TC submitted only to thermal mission
 - Good agreement of computed wrt measured values
 - Satisfactory mechanical behaviour under reentry environment, with MOS > 2.54 (compression) or MOS > 2.93 (tensile strength)

Entry Qualification Test (EQT) EADS-ST IR + mechanical facility



**Picture of EQT device
(model before AQ60 integration)**

- ⇒ **Complete structural model partially covered with TP**
- ⇒ **Heating on Front face (0 to ~1000 kW/m² in 45 sec)**
- ⇒ **Cold conditions on back face (~-60°C @ t₀)**
- ⇒ **Mechanical loading : 2 applied qualification levels : 1.4 and 2.0**
- ⇒ **Controlled N₂ atmosphere**
 - **Good correlation of thermal model & no overheating of structure**
 - **No mechanical damage of the TPS**
 - **No AQ60 or bonding mechanical failure**